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Onset of thermoacoustic oscillations in flexible transfer lines for liquid helium

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Abstract

Thermoacoustic oscillations in flexible transfer lines result in an increased evaporation rate of stored cryogen. This kind of oscillation is barely regarded since it only occurs in idle state, i.e. no liquid helium is transferred and a considerable part of the transfer line is close to ambient temperature. The examination of prototype transfer lines with built-in sensors has resulted in a unique knowledge of the oscillation characteristics. As a consequence thermoacoustic oscillations are considered as a common phenomenon in idle flexible transfer lines. The presented paper discusses the conditions for the establishment and a strategy for mitigating thermoacoustic oscillations.

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Keywords: Thermoacoustics, Oscillations, Cryogenic transfer line, Liquid helium

1. Introduction

In general, thermoacoustic oscillations occur spontaneously if a half-open tube e.g. a transfer line is inserted into a liquid helium reservoir. The transfer line is open at the cold end (i.e. the liquid helium reservoir) and closed at the warm end (i. e. angle valve of the transfer line). Since the temperature at the cold open end is equal to the saturation temperature of helium and the warm end temperature is close to ambient temperature, the temperature ratio $\alpha = T_h/T_c$ is usually greater than 60 and the system will tend to oscillate. Besides the general requirements of a half-open tube and a large temperature ratio, the onset of a thermoacoustic oscillation is influenced by the transfer line geometry and the ratio between the warm and the cold length of the tube $\xi = l_h/l_c$, too. Existing publications consider the onset of thermoacoustic oscillations theoretically [1] and experimentally [2], [3] in straight, mostly uninsulated pipes. Since the geometry of a transfer line, e.g. u-bend shape, vacuum insulated pipes, differs from the simple geometry of a straight pipe the applicability of published results has to be verified. For that purpose a standard storage vessel has been equipped with an experimental transfer line of typical dimensions. The latter can be monitored during the

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transfer of liquid helium and in idle state by inbuilt temperature and pressure sensors. If thermoacoustic oscillations do occur in liquid helium transfer lines their impact on the stored cryogen has to be considered. This concerns mainly the increased evaporation rate which results in a greater re-liquefaction effort. Besides that a steeper rise of the storage pressure might cause safety issues if not detected. Furthermore, a strategy to reduce the intensity of thermoacoustic oscillations is presented which does only require minor modifications of the transfer line design.

2. Experimental setup

In order to examine the onset of thermoacoustic oscillations in cryogenic transfer lines, a liquid helium storage vessel of 2.5 m^3 capacity has been equipped with an experimental transfer line whose detailed description is published in [4]. The transfer line consists of two rigid vertical and one flexible horizontal sections. Its flexibility is achieved by a corrugated tube with an inner diameter of 8.3 mm. The rigid conduits inner diameter is 6 mm whereas the corresponding outer pipe has a diameter of 12 mm. A pneumatically actuated angle valve is located at the end of the flexible section. The experimental transfer line can be equipped with an optional spring-loaded foot valve at the inlet to examine its influence on the onset of thermoacoustic oscillations during idle state. In idle state no liquid helium is transferred and the line is allowed to warm up.

The applied in-line pressure transmitters and temperature sensors are numbered according to their appearance in the flow direction (see Figure 1a). Pressure transmitter 1 is located at the upper end of the first vertical section. Transmitter 2 is situated right before and transmitter 3 right after the flexible horizontal section. The temperature sensors 1 to 3 are numbered and positioned accordingly. The temperature sensor labeled T_{in} is located 260 mm from the inlet of the transfer line. All temperature values are acquired with a frequency of 0.25 Hz whereas the pressure signals are acquired with a sampling rate of 500 Hz. The applied pressure transmitters have a maximum error band of ± 0.1 % and a range of 80 kPa_g. All pressure transmitters are connected with the inner conduit of the transfer line via capillaries. During the commissioning of the experimental transfer line measurements were conducted to ensure that these capillaries do neither influence the onset of thermoacoustic oscillations nor dampen the achieved pressure signals. Silicon diodes type DT-670-SD, having a measurement error of ± 0.25 K, are applied to the outer wall of the inner conduit.

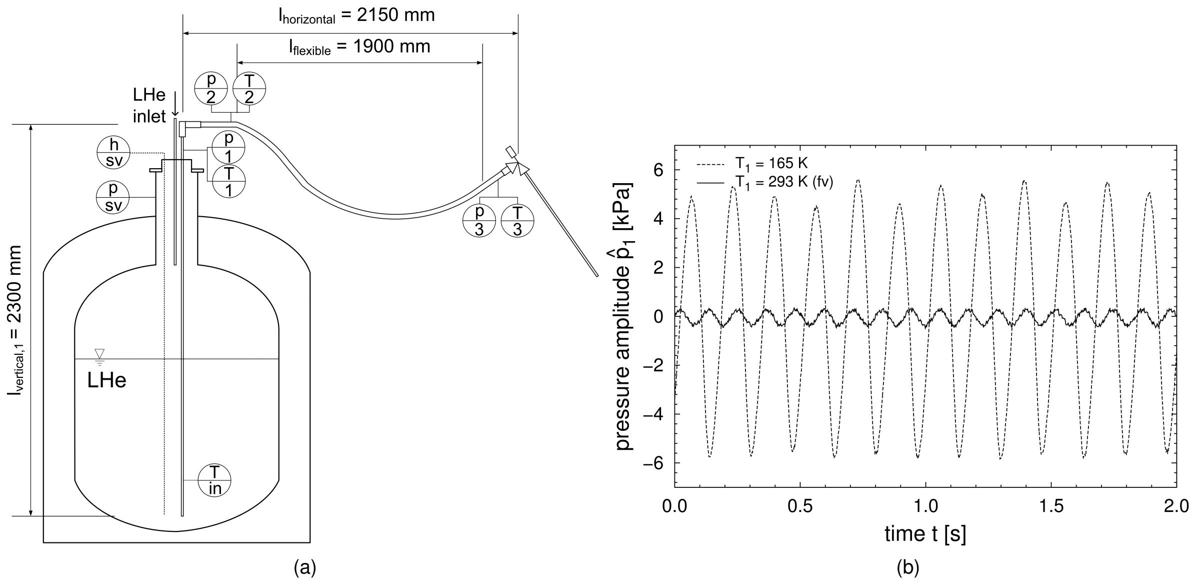


Fig. 1: (a) Scheme of the test setup at the liquid helium decant station (all horizontal dimensions refer to an elongated line); (b) Pressure amplitudes of a thermoacoustic oscillation at different temperatures T_1 (abbreviation *fv* indicates that values are achieved with an continuously opened foot valve installed at the transfer line inlet).

3. Results and discussion

3.1. Onset of thermoacoustic oscillations

The experimental results have shown that thermoacoustic oscillations are observed in liquid helium transfer lines in idle state (see Figure 1b). After closing the angle valve to stop the liquid helium transfer, the line warms up rather rapidly due to heat leak from the ambiance. The corresponding mean temperature rise is determined to be around 3.5 K/min. If a transfer line without a foot valve is considered two oscillation modes are observed. First, a low amplitude oscillation with a pressure amplitude of 0.4 to 0.7 kPa is established at T_1 = 100 to 120 K (α_1 = 24 to 29). At a temperature of T_1 = 220 to 250 K (α_1 = 52 to 60) the amplitude increases suddenly to 2.8 kPa, which represents the second oscillation mode. The maximum amplitude of 5.6 kPa is achieved at a minimum temperature of T_1 = 161 K. It has to be remarked that the absolute pressure in the transfer system ranges between 0.13 and 0.14 MPa. Therefore the observed pressure amplitudes are rather significant compared to the mean pressure in the transfer system. If a continuously opened foot valve is installed at the inlet only low pressure amplitudes are observed.

Figure 2 indicates the behaviour of temperature and amplitude as a function of time. Although a low amplitude oscillation is observed rather soon after the end of a liquid helium transfer, the temperature T_1 rises constantly until a critical temperature of 220 to 250 K is reached. Afterwards temperature T_1 decreases due to the increased heat transfer caused by the amplified thermoacoustic oscillation which causes the length ratio $\xi = l_h/l_c$ to decrease as well. Since the pressure amplitude correlates with ξ (according to [2]) the thermoacoustic oscillation is amplified while the cold length increases. Figure 4a indicates that at the minimum value of T_1 the value of ξ is close to unity and the boundary between the warm and the cold section is located outside of the storage vessel. At ξ close to unity the driving force of the thermoacoustic oscillation i.e. the heat transfer area is reduced whereas the inertial force increases, both limiting the observed amplification. The inertial force of the considered system is dominated by the mass of the oscillating cold gas column. The oscillation tends to be damped at $\xi = 1$ and T_1 rises again. Close to the critical temperature the oscillation is amplified again but with a lower pressure amplitude and temperature drop. The amplification is continuously reduced by the greater viscous resistance of the warm gas column since the mean temperature of the warm gas column approaches ambient temperature. The viscous resistance is dominated by the warm section since the kinematic viscosity of the warm gas is four magnitudes greater than that of the cold gas [5]. In idle state the cycle of amplified and damped oscillations is observed several times but with a continuously decreasing amplification. During a very long idle time temperature T_1 finally approaches ambient temperature, too. At the same

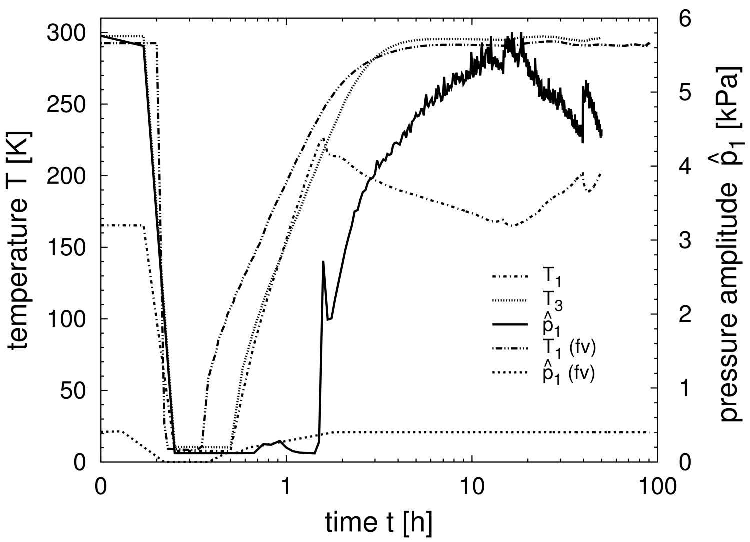


Fig. 2: Time-referenced values of temperature and amplitude during the onset of thermoacoustic oscillations.

time the boundary between the cold and the warm length of the transfer line is shifted towards the liquid helium reservoir. At $T_1 \approx 300$ K the length ratio ξ is close to 5 which means that the boundary between the warm and the cold length is close to the transfer line inlet. At this condition only a small amplitude similar to that obtained with a continuously opened foot valve is observed (see Figure 4a). As the pressure amplitude decreases with increasing values of ξ the frequency increases slightly from 6 to 9 Hz.

3.2. Temperature profile

Measurements published in [3] indicate that the temperature profile between the warm and cold section can be described by a s-shape function with a rather steep sloop. Since the distances between the installed temperature sensors are rather large the slope of the temperature profile has to be approximated. In order to do this a logistic distribution of the dimensionless temperature $\theta = T(z)/T_{amb}$:

$$\theta(z) = \left(1 + exp\left(-\frac{\sigma_z - \sigma_c}{\beta}\right)\right)^{-1}, \tag{1}$$

with σ being the dimensionless axial position, σ_c being the location of the distribution's inflection point and β being a parameter of the logistic distribution, is chosen. According to [1] the boundary between the cold and the warm length is defined by the axial position of the distribution's inflection point. The temperature at the inlet is assumed to be equal to the helium saturation temperature since the inlet is always kept below the liquid level.

It can be derived from Figure 3 that the temperature profile of the gas column inside the transfer line is rather steep, especially in the case where low amplitudes are observed. Since the cold length is small compared to the warm length the viscous resistance dampens the thermoacoustic oscillation although a steep temperature profile promotes the onset of a thermoacoustic oscillation generally. If the highest pressure amplitudes are observed the temperature profile approaches a linear one which effectively dampens the oscillation. If a foot valve is applied and kept open only low pressure amplitudes between 0.3 and 0.6 kPa are observed. Any amplification is prevented by the foot valve which both increases the turbulent loss coefficient at the inlet and reduces the intensity of the heat exchange between the gas column and the stored liquid helium.

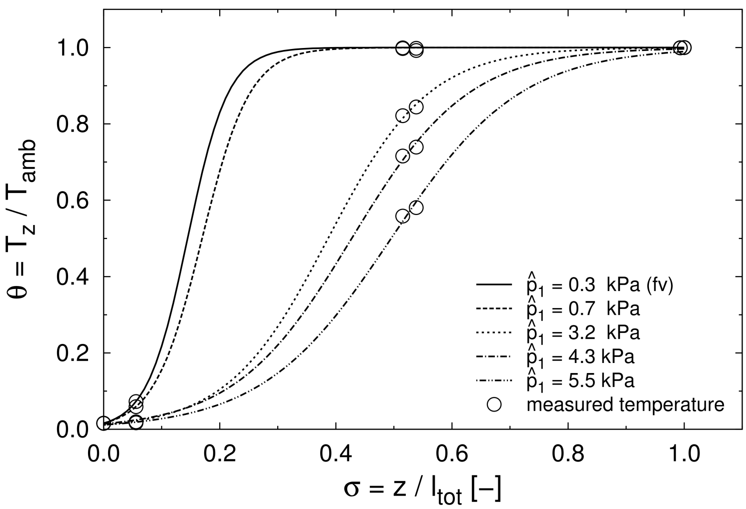


Fig. 3: Approximated temperature profiles for selected pressure amplitudes.

3.3. Estimation of frequency and pressure amplitude for a given system

The pressure amplitude of the considered thermoacoustic oscillation can be calculated if it is considered as a system consisting of a spring, a mass and a turbulent damper. In this case the oscillating mass is represented by the cold gas column whereas the warm gas acts as a spring. According to [2] the pressure amplitude $\hat{p}$ in a free oscillator is mainly determined by the gas properties and the geometry of the free oscillator system, i.e. the transfer line:

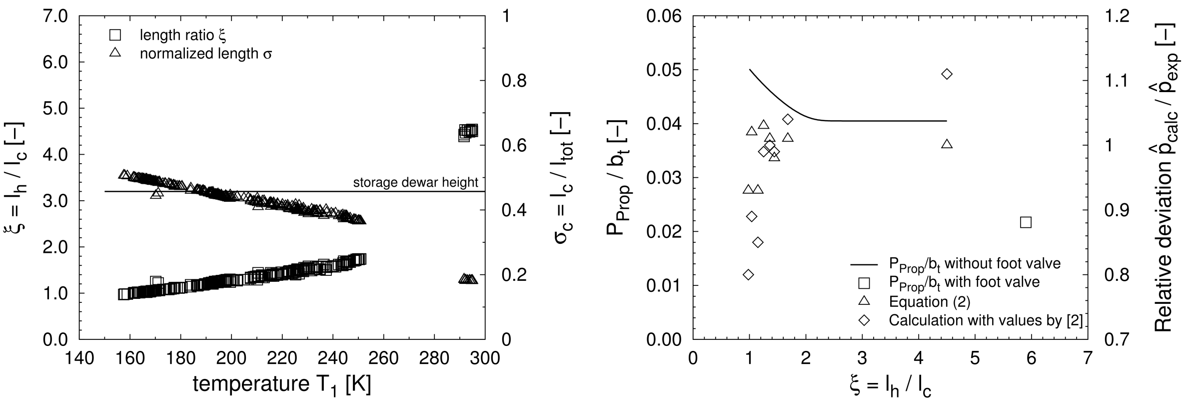
$$\hat{p} = \frac{3 \cdot \pi \cdot V_{wg} \cdot k^3 \cdot r_i^2}{4 \cdot A^3 \cdot \omega^3 \cdot \eta_{cg} \cdot l_{tot}^2} \cdot \frac{P_{Prop}}{b_t} \tag{2}$$

where V_{wg} is the volume of the trapped gas in the warm section of the transfer line, A is the area at the boundary between the warm and the cold length, η_{cg} is the viscosity of the cold gas, l_{tot} is the the total distance between the open and closed end and k is the spring constant related to the warm gas section. The ratio P_{Prop}/b_t is specific for each oscillating system and has to be determined accordingly. P_{Prop} is a proportionality factor in the calculation of the power of the thermoacoustic drive. Since in the case of a free oscillator the pressure amplitude and the frequency are rather important, the thermoacoustic power is not considered subsequently. The turbulent loss coefficient b_t comprises turbulent losses at the open end of the tube and due to the elbow of the transfer line. Since this value cannot be determined experimentally with the given setup, only the relative ratio P_{Prop}/b_t is given in this paper (see Figure 4b). For a rough estimation published values of P_{Prop} and b_t in [2] give good results, too. For large values of ξ the factor P_{Prop} tends to approach a constant value. Thus, an opened foot valve at the inlet increases the turbulent loss coefficient by a factor of two. An assumption of the frequency is necessary to solve equation (2) in order to estimate the expected pressure amplitude of a given transfer line. A good estimation can be achieved by calculating the dimensionless quantity according to [1]:

$$Y_c \cdot \lambda_c^{-0.5} = \left(\frac{a_{cg} \cdot \rho_{cg}}{\eta_{cg}}\right)^{0.5} \cdot \frac{r_i}{l_c}, \tag{3}$$

where a_{cg} is the speed of sound, ρ_{cg} is the cold gas density and r_i the radius of the tube. The related dimensionless frequency $\lambda_c = \omega \cdot l_c/a_{cg}$ can be derived from Figure 5 in [1]. For $\xi = 1$ and 2 the frequency is determined to be 6 and 7 Hz, respectively. The observed frequency increase at low pressure amplitudes is in good agreement with Rott's theory, too. It gives a frequency of 9 Hz for $\xi = 5$ which is the approximate length ratio for a low amplitude oscillation.

Experimental results have shown that the thermoacoustic oscillation is independent of the liquid level in the storage vessel. Furthermore, the mean value of the static pressure in the transfer line is related directly to the liquid level which



(a) (b)

Fig. 4: (a) Normalized length σ and length ratio ξ as derived from Figure 3; (b) Ratio of P_{Prop}/b_t.

indicates that large parts of the insulated line are filled with gaseous helium. An increase of the inlet temperature to 20 to 30 K right after closing the angle valve approves this assumption. The inlet temperature decreases to the saturation temperature only in the case of a high amplitude oscillation indicating an increased heat exchange between the oscillating gas and the stored liquid helium. Therefore, it can be stated that the inertial forces of a helium transfer system are mainly influenced by the oscillating cold gas column.

3.4. Heat leak

Heat leak values for different oscillation modes were calculated and listed in Table 1 assuming an isochoric change of state during the pressure rise in the storage vessel. It can be concluded that a high amplitude increases the overall heat leak by a factor of two resulting in an overall evaporation rate of 2.6 l_{LHe} per hour. The additional heat leak caused by low amplitude oscillations can be neglected since the overall heat leak is close to that of the vessel itself.

Table 1: Values of the overall heat leak and the evaporation rate of the given liquid helium storage vessel.

Value \ Oscillation mode	High amplitude	Low amplitude	Storage vessel only
Total heat leak $\dot{Q}_{tot}$ [W]	22.5 (± 0.82)	14.9 (± 0.30)	12 (± 1.35)
Evaporation rate ΔV_l [l_{LHe}/h]	2.6	1.1	1.0

4. Conclusion

Experimental results have shown that a transfer line for liquid helium tends to oscillate in idle state at rather high pressure amplitudes. As a consequence, the overall heat leak into the storage vessel nearly doubles which increases the evaporation rate significantly. The time-referenced pressure rise increases sharply if the generated helium gas cannot be discharged sufficiently, resulting in critical values of the storage pressure. Thus, thermoacoustic oscillations are a severe problem concerning the safety and the efficiency of storage vessels at liquid helium decant stations. One promising approach to mitigate these oscillations is the installation of a continuously opened foot valve at the transfer line inlet which prevents the amplification of low amplitude oscillations at any time. The additional heat leak and the resulting pressure rise of low amplitude oscillations can be neglected since they are in the order of typical values related to bare storage vessels. Although the theory of thermoacoustic oscillations is quite complex, the achieved experimental results and the results gained by published correlations are in good accordance. By using thermophysical properties of the cold and warm gas column the characteristic values of a thermoacoustic oscillation, mainly the pressure amplitude and frequency, can be estimated quite accurate.

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